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(54) **HANDHELD ELECTRONIC DEVICES WITH ISOLATED ANTENNAS**

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Related U.S. Application Data

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H01Q 1/24 (2006.01)

(52) **U.S. Cl.** .... **343/702**; 343/700 MS

(58) **Field of Classification Search** 343/702, 343/700, 725, 767, 829, 846
See application file for complete search history.

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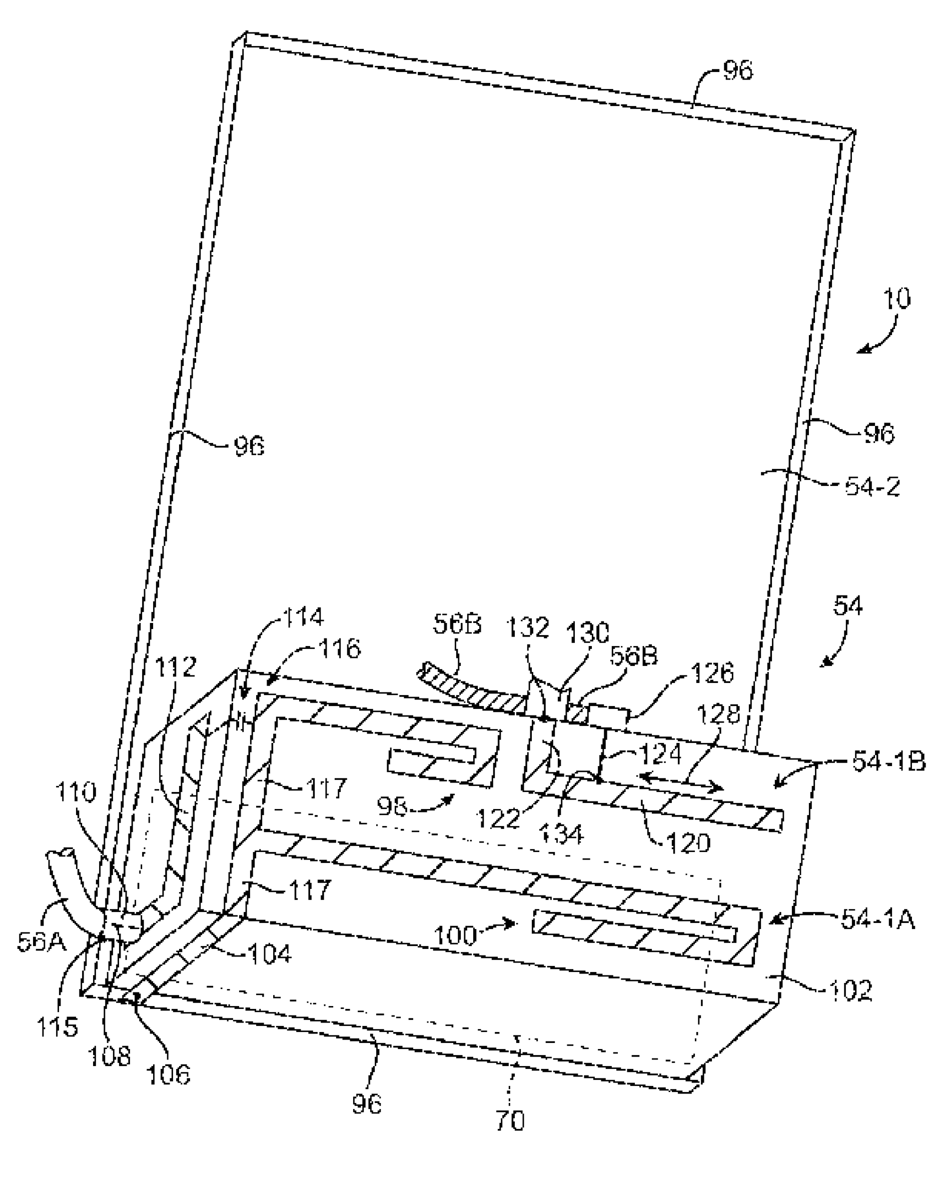
(74) *Attorney, Agent, or Firm*—Treyz Law Group; G. Victor Treyz; David C. Kellogg

(57) **ABSTRACT**

Handheld electronic devices are provided that contain wireless communications circuitry having at least first and second antennas. An antenna isolation element reduces signal interference between the antennas, so that the antennas may be used in close proximity to each other. A planar ground element may be used as a ground by the first and second antennas. The first antenna may be formed using a hybrid planar-inverted-F and slot arrangement in which a planar resonating element is located above a rectangular slot in the planar ground element. The second antenna may be formed from an L-shaped strip. The planar resonating element of the first antenna may have first and second arms. The first arm may resonate at a common frequency with the second antenna and may serve as the isolation element. The second arm may resonate at approximately the same frequency as the slot portion of the hybrid antenna.

5 Claims, 12 Drawing Sheets



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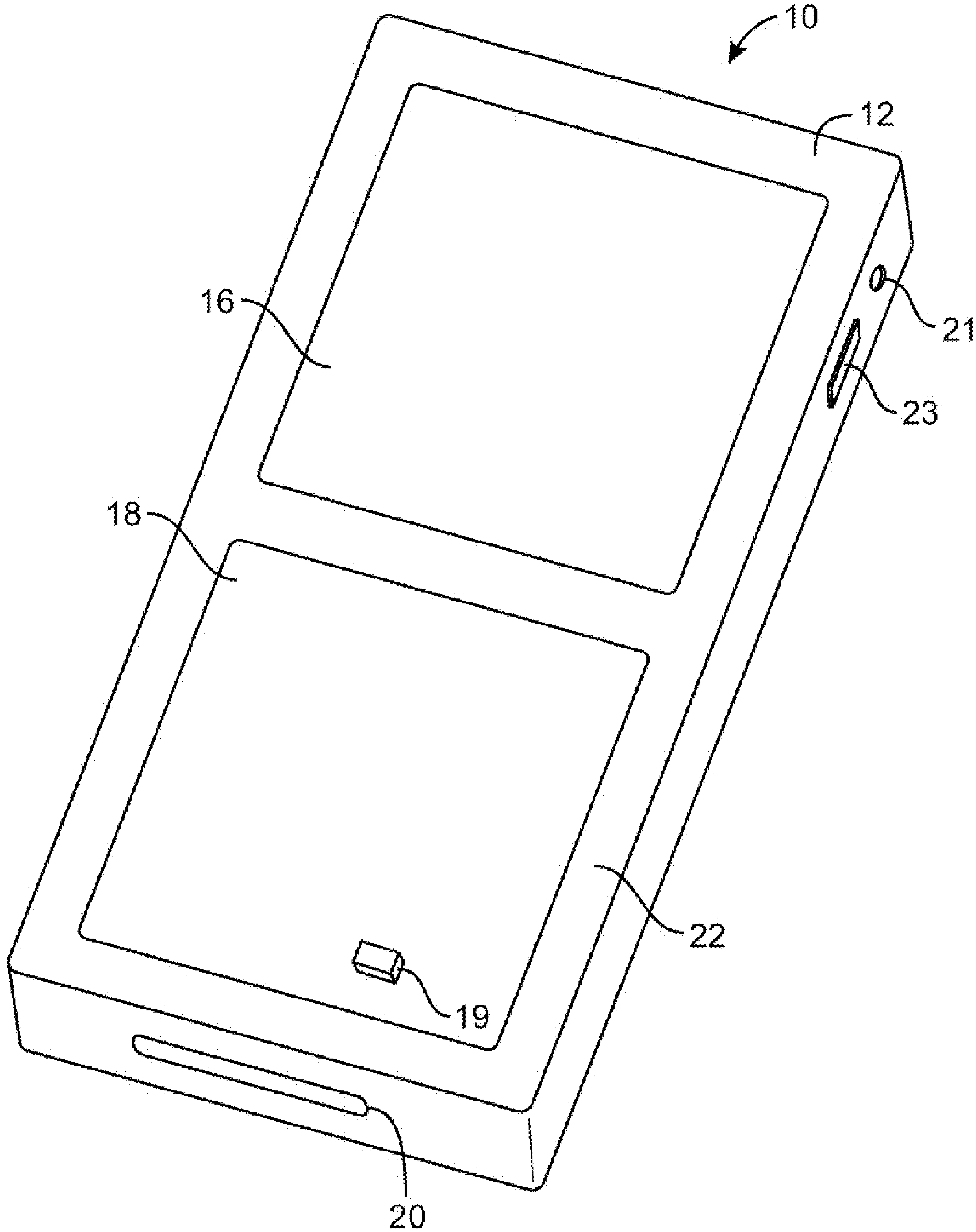


FIG. 1

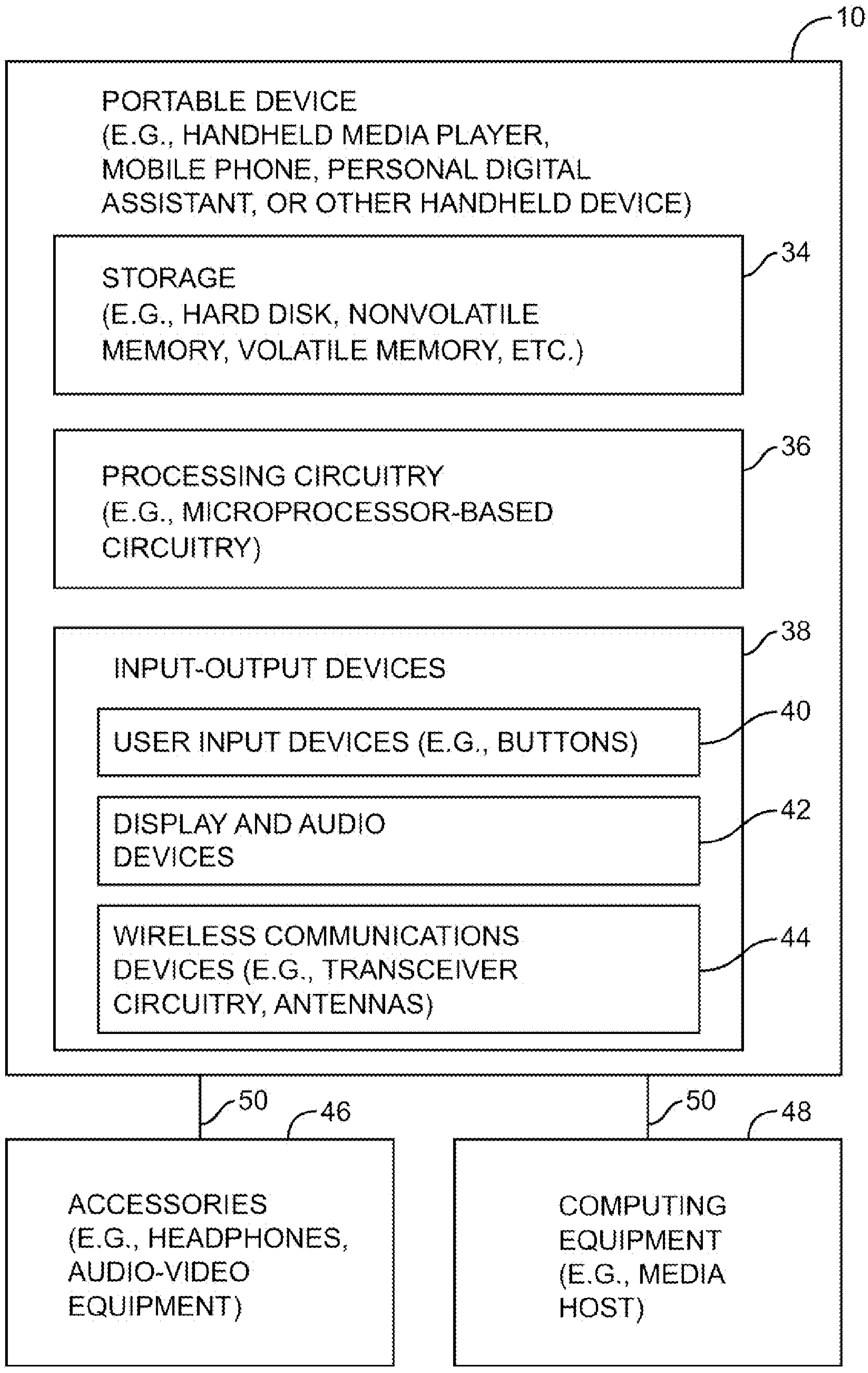

10
PORTABLE DEVICE
(E.G., HANDHELD MEDIA PLAYER,
MOBILE PHONE, PERSONAL DIGITAL
ASSISTANT, OR OTHER HANDHELD DEVICE)
34
STORAGE
(E.G., HARD DISK, NONVOLATILE
MEMORY, VOLATILE MEMORY, ETC.)
36
PROCESSING CIRCUITRY
(E.G., MICROPROCESSOR-BASED
CIRCUITRY)
38
INPUT-OUTPUT DEVICES
40
USER INPUT DEVICES (E.G., BUTTONS)
42
DISPLAY AND AUDIO
DEVICES
44
WIRELESS COMMUNICATIONS
DEVICES (E.G., TRANSCEIVER
CIRCUITRY, ANTENNAS)
50
46
50
48
ACCESSORIES
(E.G., HEADPHONES,
AUDIO-VIDEO
EQUIPMENT)
COMPUTING
EQUIPMENT
(E.G., MEDIA
HOST)

FIG. 2

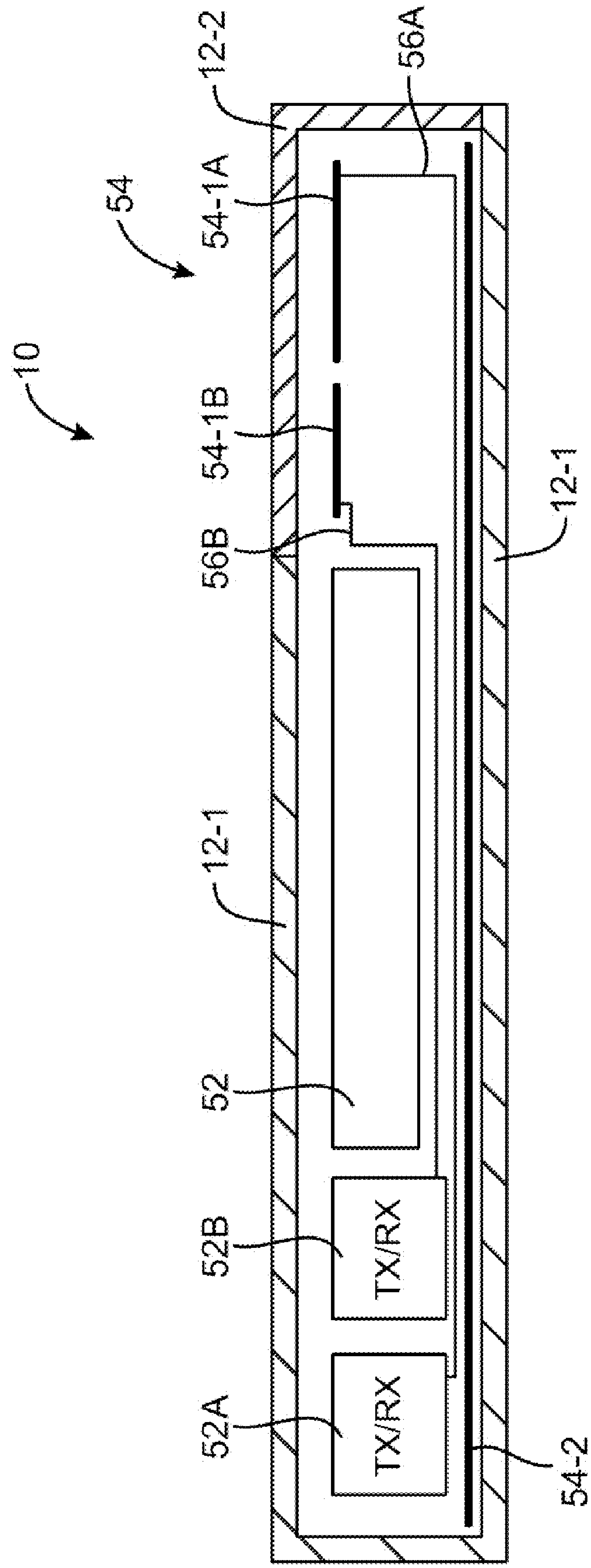


FIG. 3A

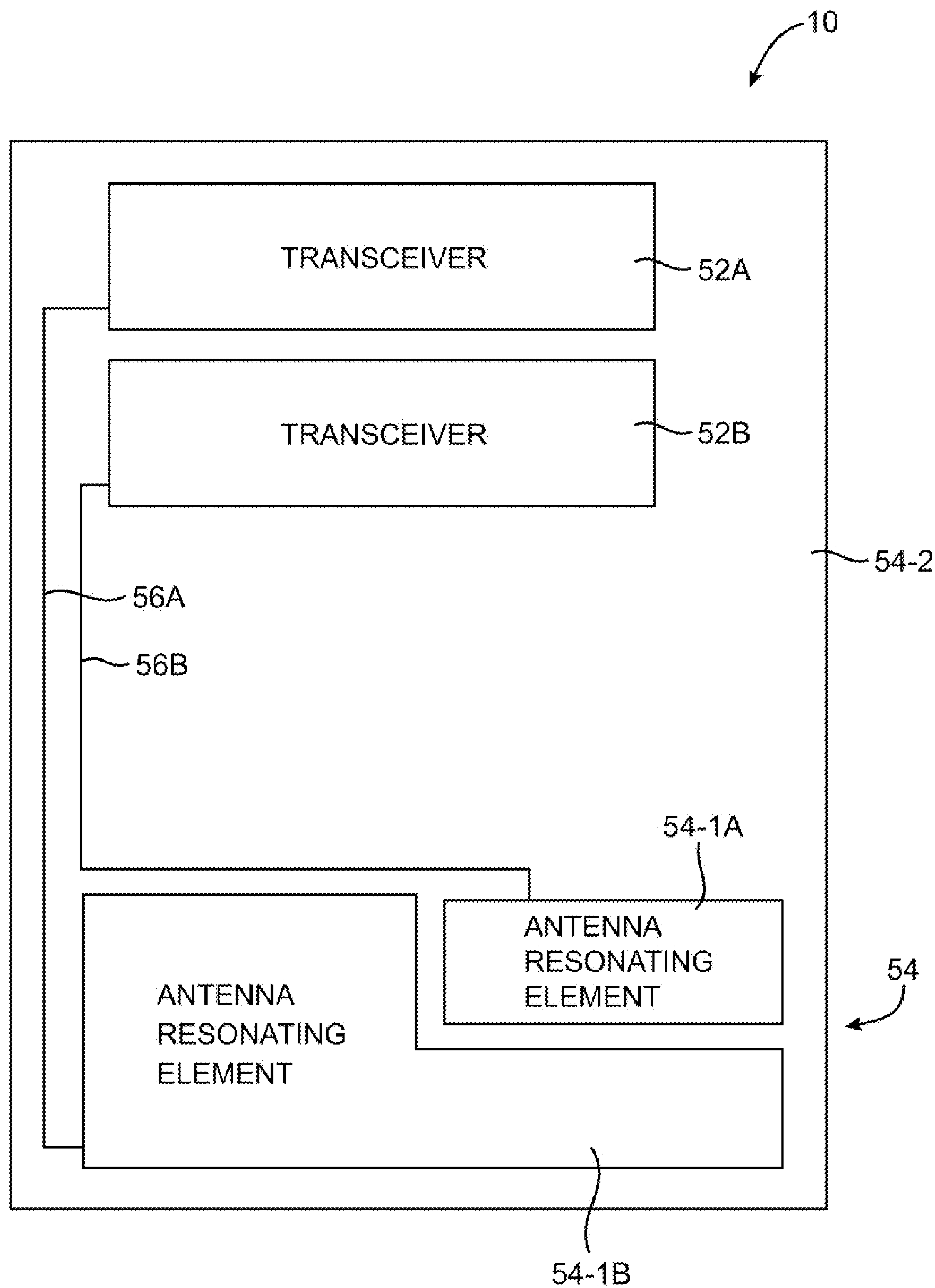

10
TRANSCEIVER
52A
TRANSCEIVER
52B
54-2
56A
56B
54-1A
ANTENNA
RESONATING
ELEMENT
54
ANTENNA
RESONATING
ELEMENT
54-1B

FIG. 3B

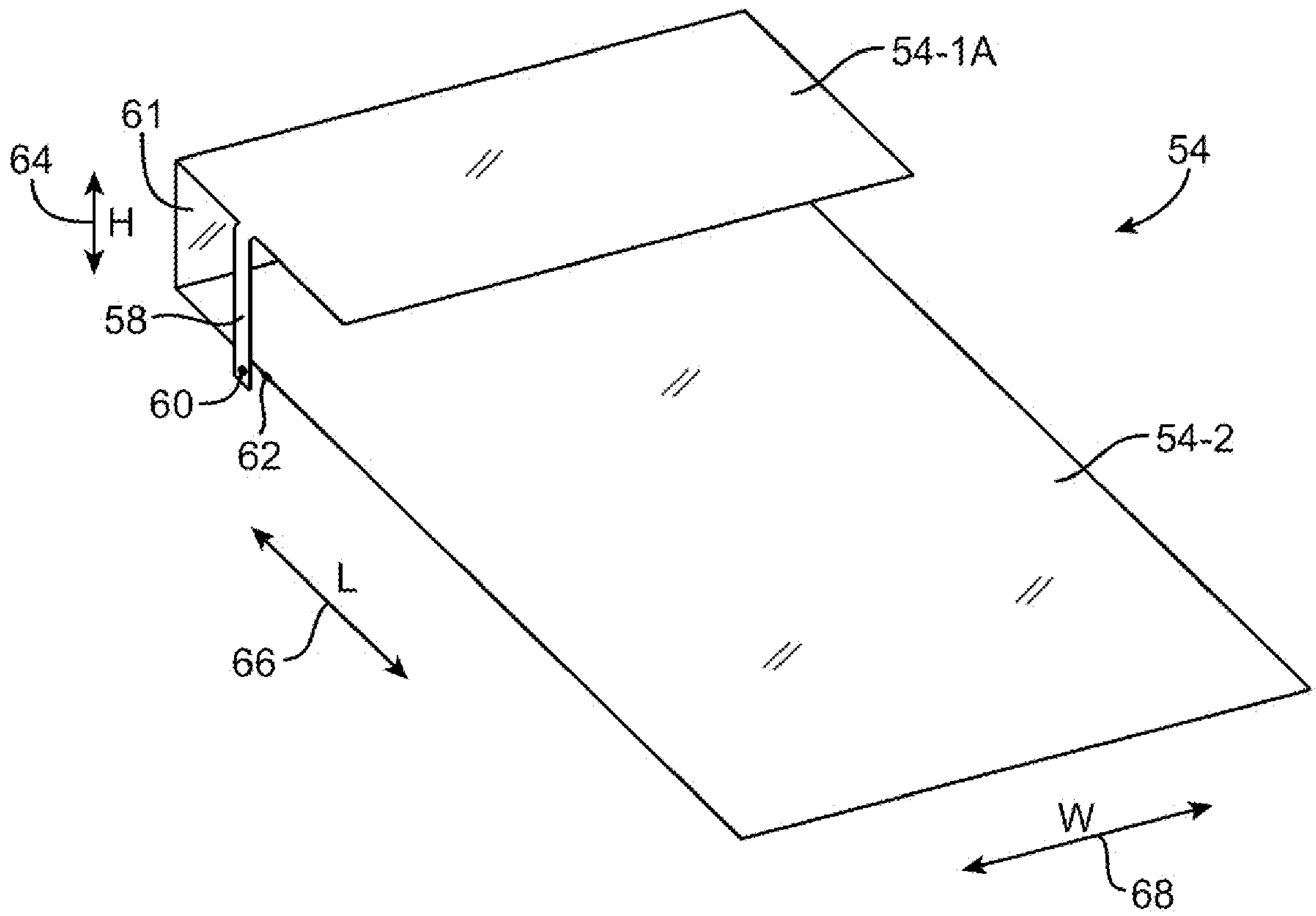


FIG. 4

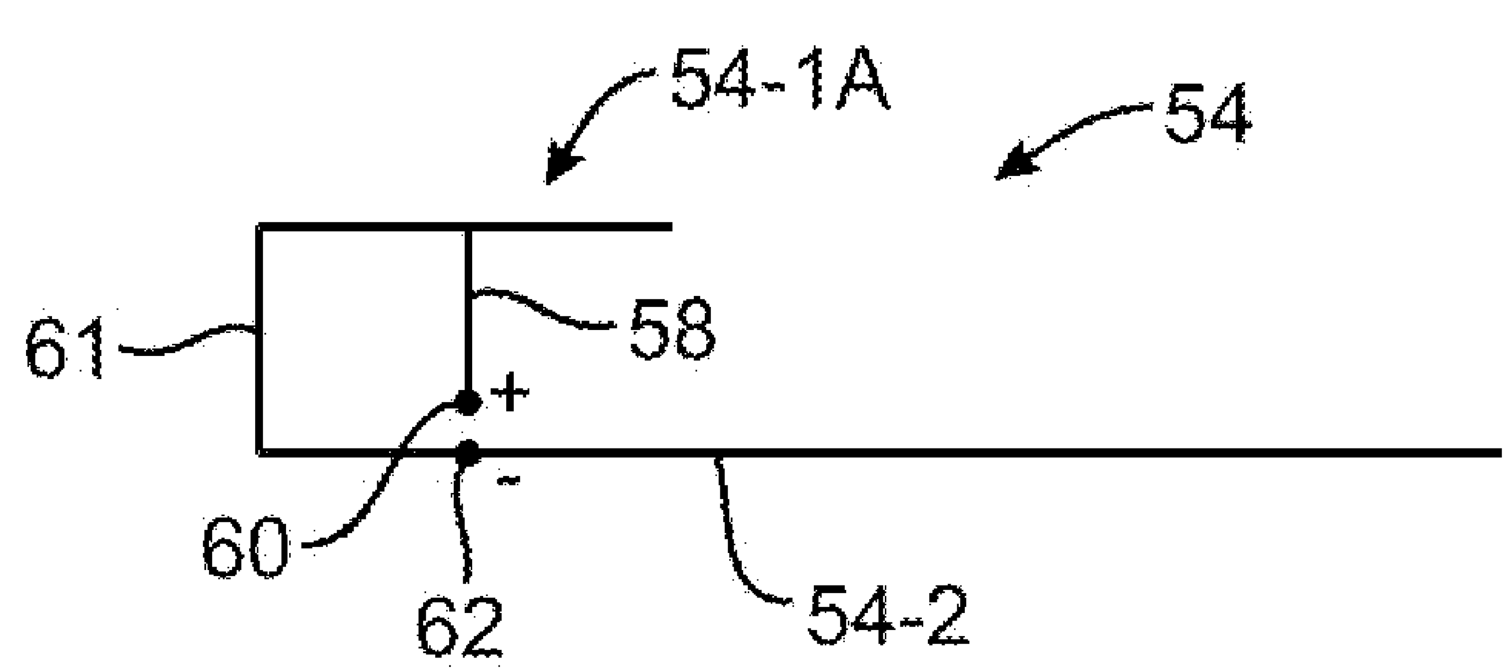


FIG. 5

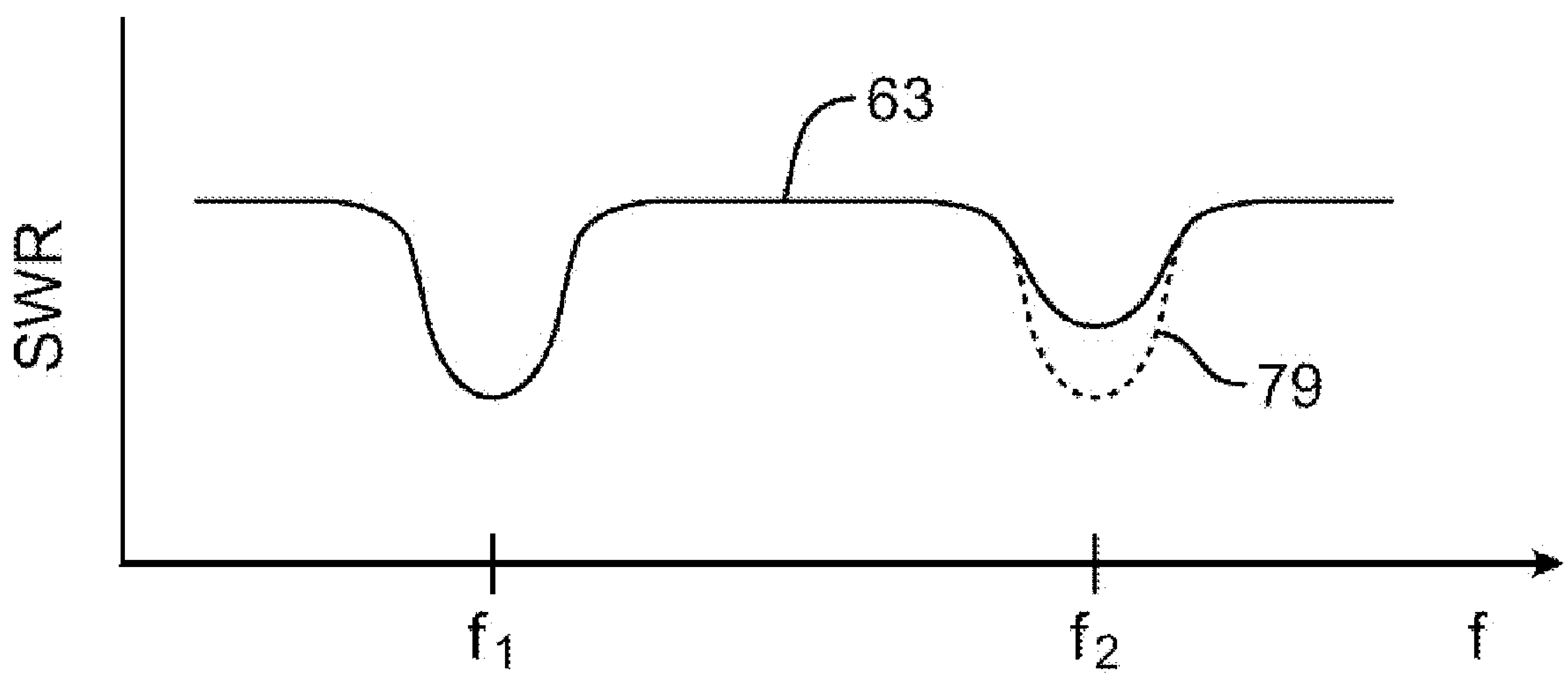


FIG. 6

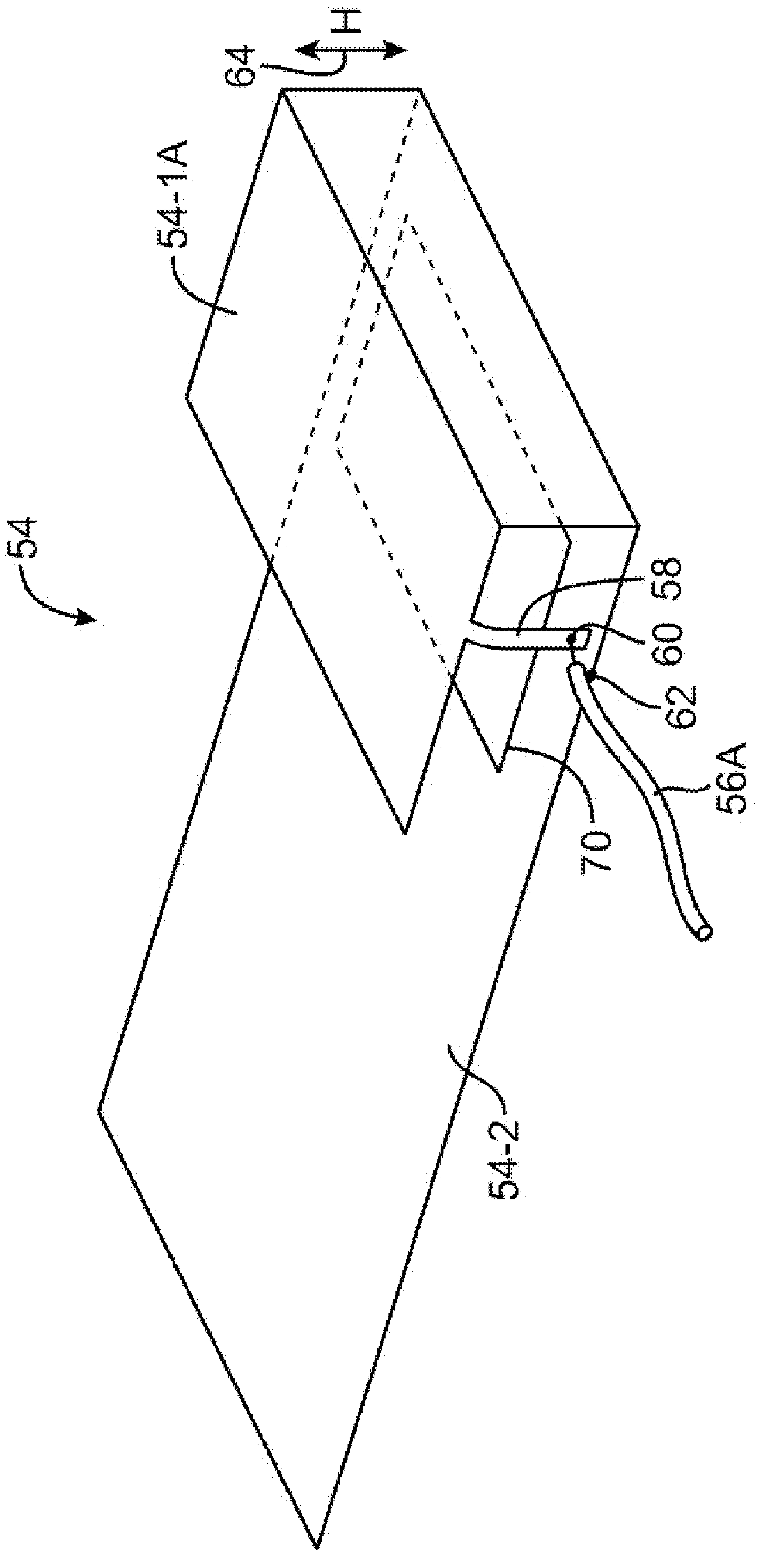


FIG. 7

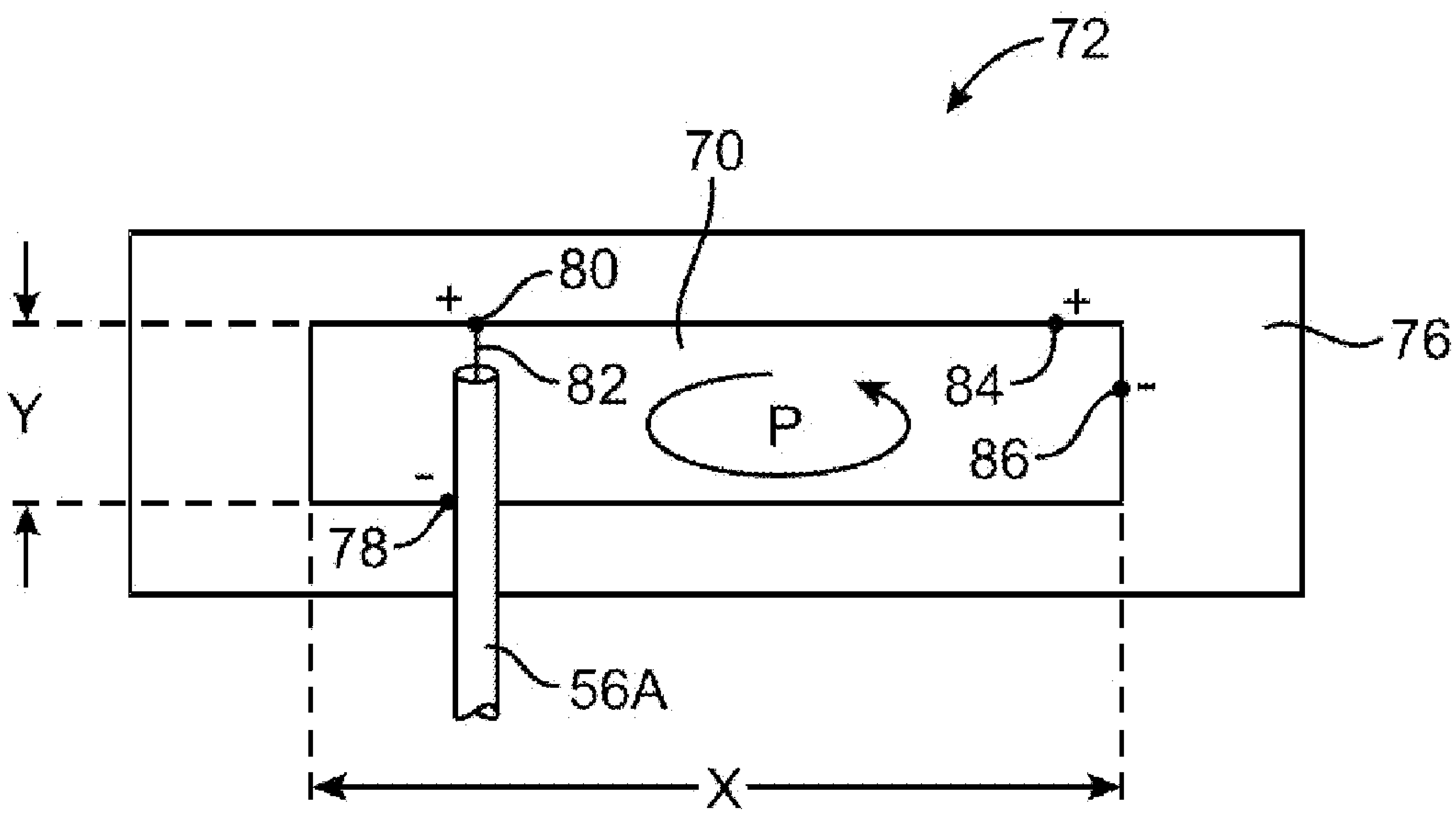


FIG. 8

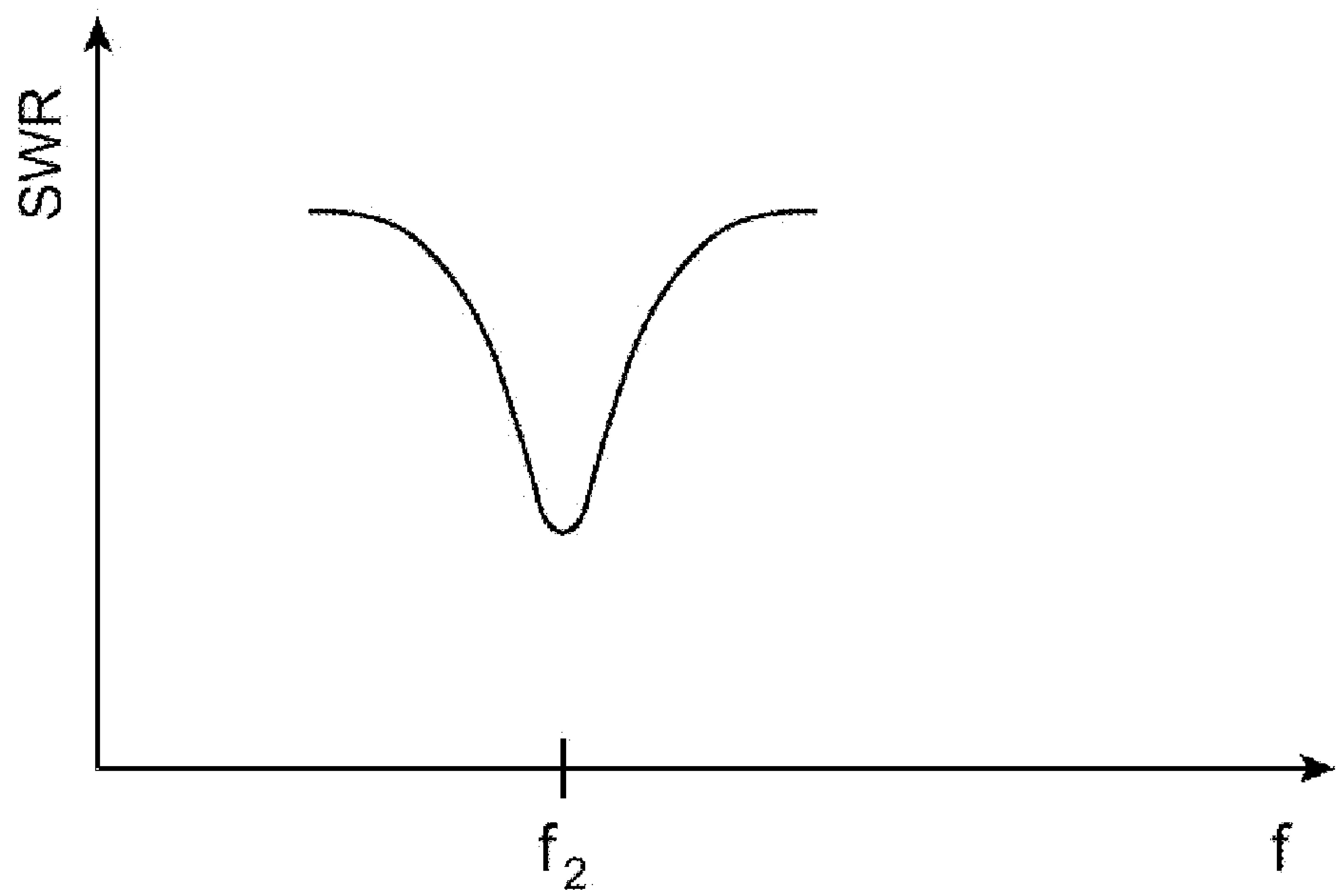


FIG. 9

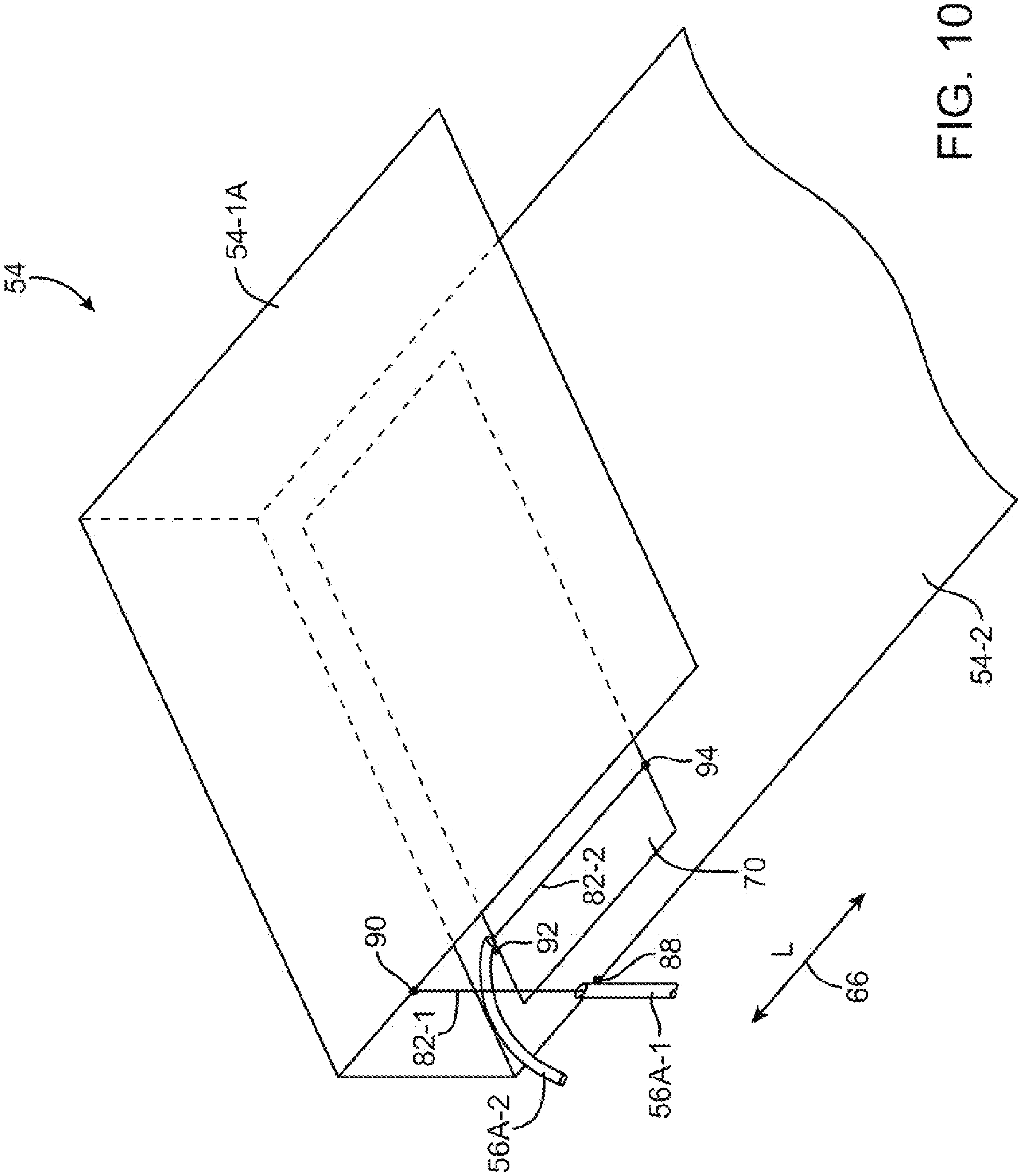


FIG. 10

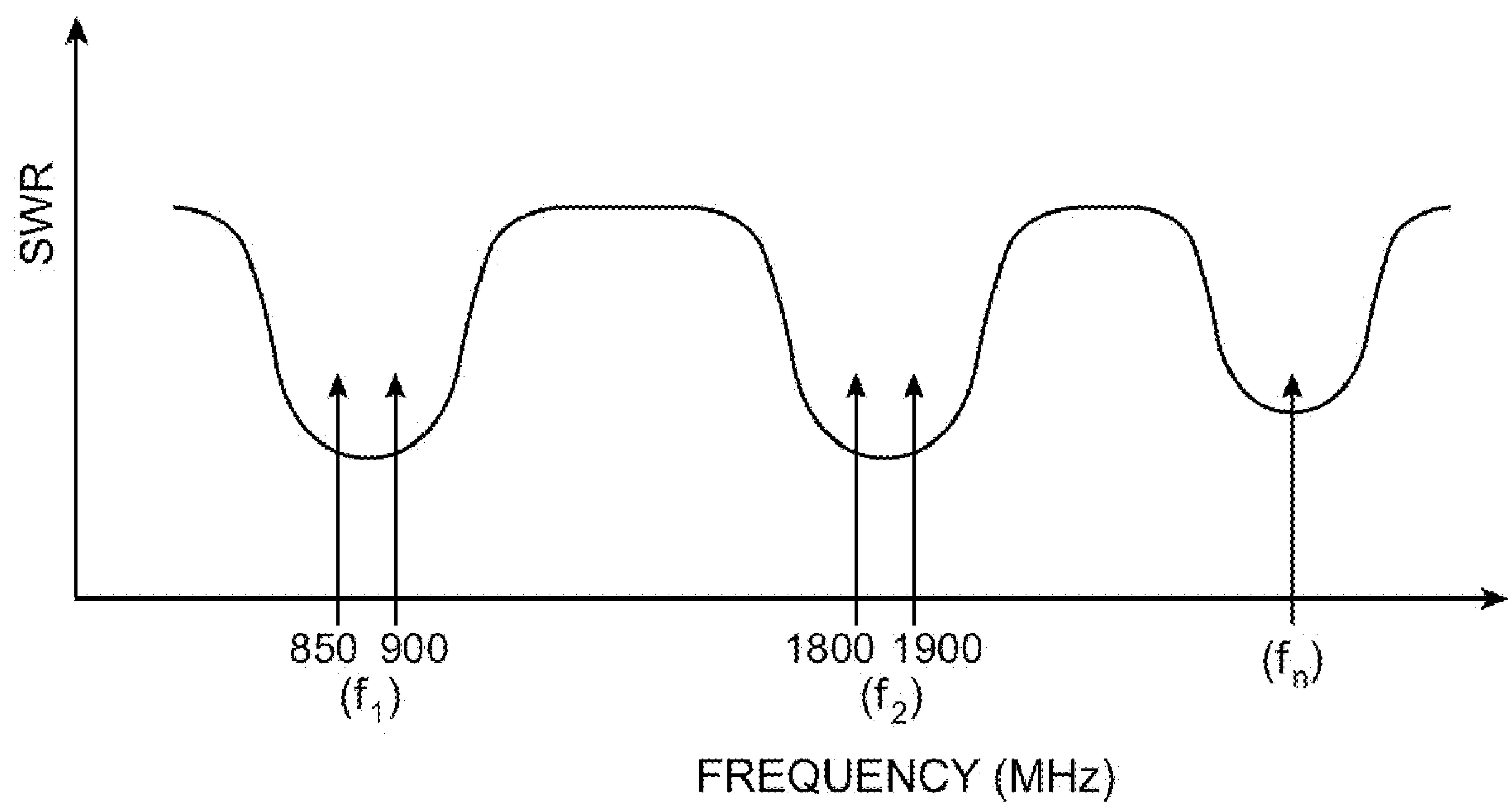
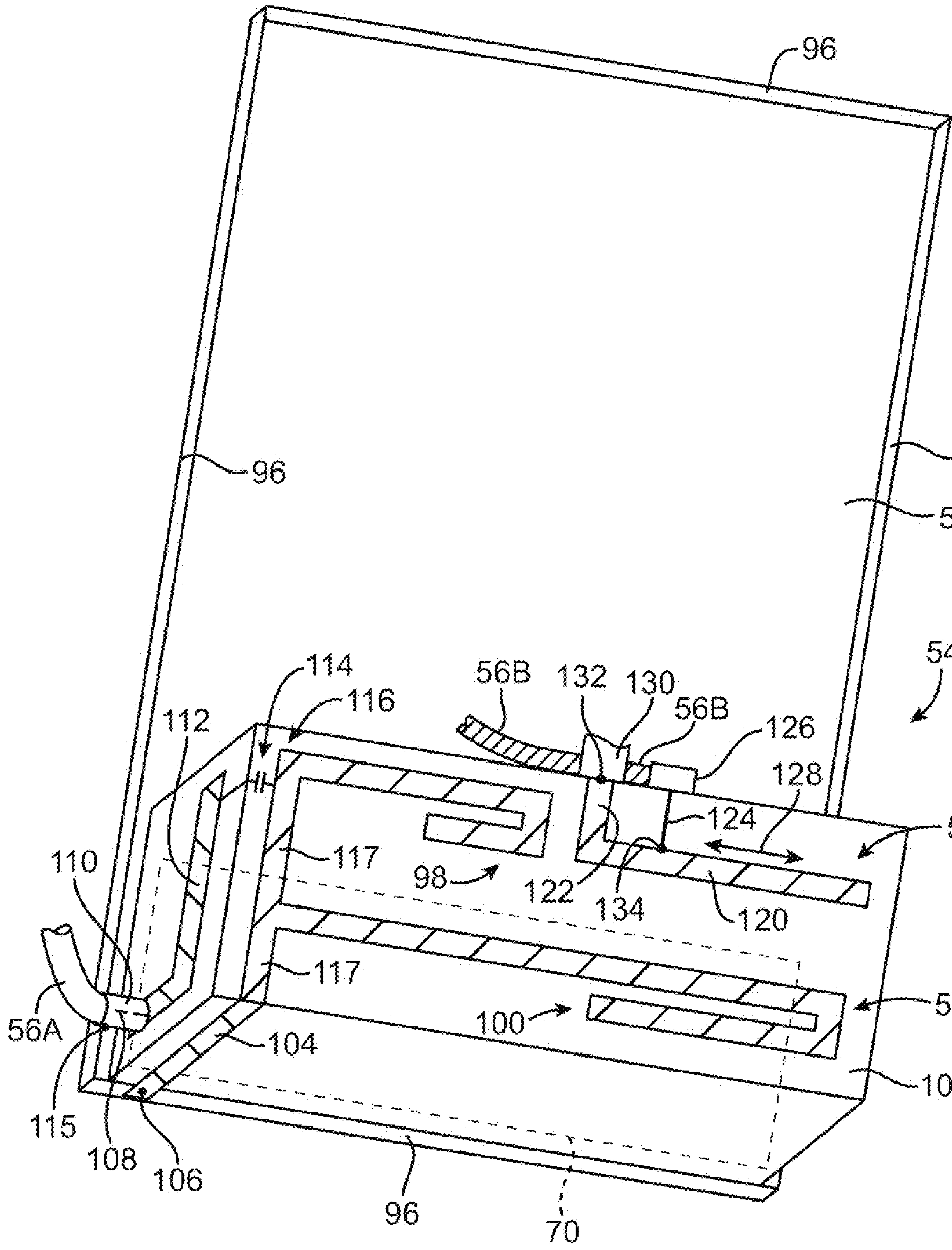


FIG. 11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70

FIG. 12

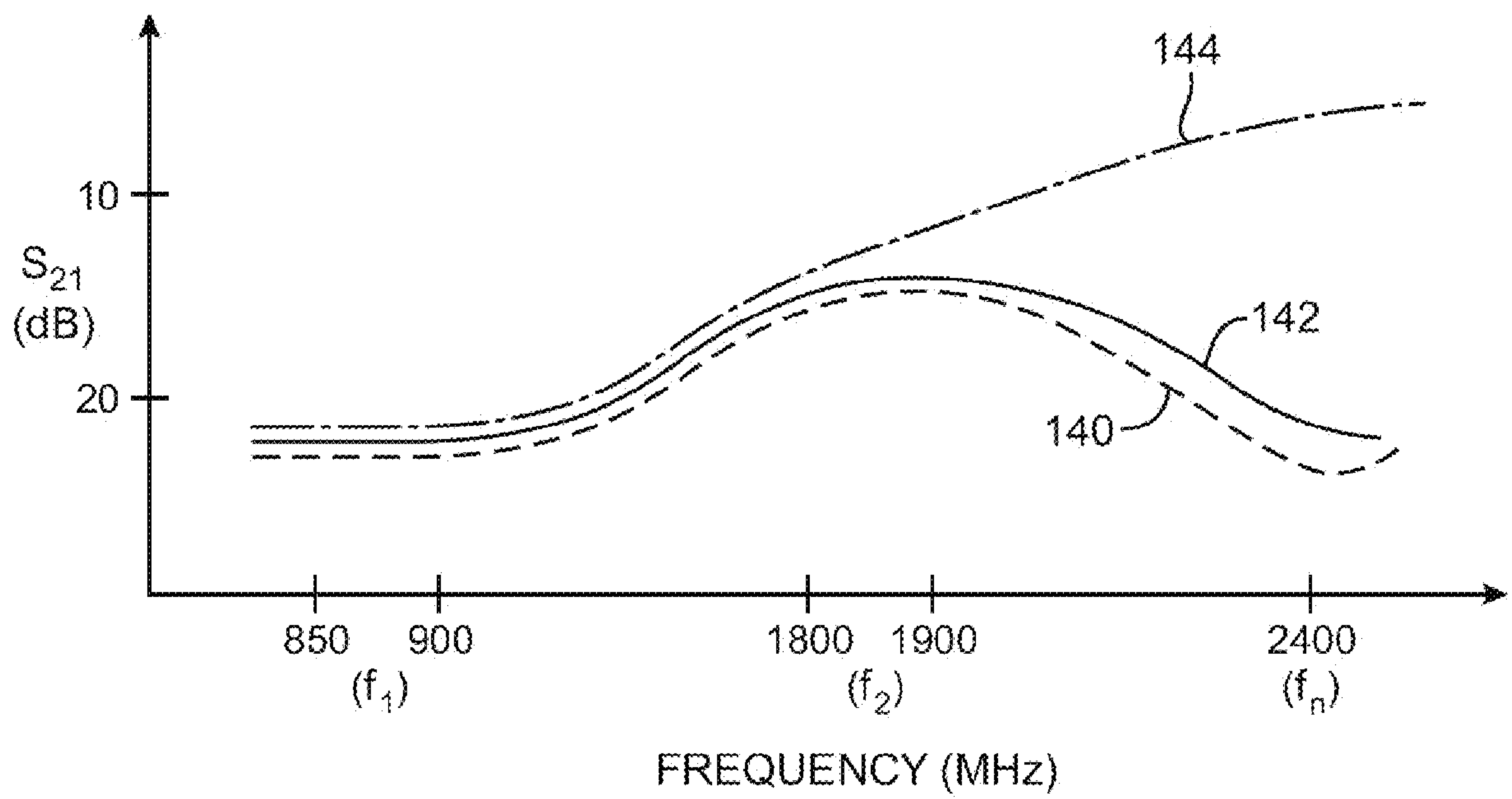
144
10
S_{21}
(dB)
142
20
140
850
(f1)
900
1800
(f2)
1900
2400
(fn)
FREQUENCY (MHz)

FIG. 13

HANDHELD ELECTRONIC DEVICES WITH ISOLATED ANTENNAS

This application is a division of patent application Ser. No. 11/650,071, filed Jan. 4, 2007, now U.S. Pat. No. 7,595,759 which is hereby incorporated by reference herein in its entirety.

BACKGROUND

This invention relates generally to wireless communications circuitry, and more particularly, to wireless communications circuitry for handheld electronic devices.

Handheld electronic devices are becoming increasingly popular. Examples of handheld devices include handheld computers, cellular telephones, media players, and hybrid devices that include the functionality of multiple devices of this type.

Due in part to their mobile nature, handheld electronic devices are often provided with wireless communications capabilities. Handheld electronic devices may use wireless communications to communicate with wireless base stations. For example, cellular telephones may communicate using cellular telephone bands at 850 MHz, 900 MHz, 1800 MHz, and 1900 MHz (e.g., the main Global System for Mobile Communications or GSM cellular telephone bands). Handheld electronic devices may also use other types of communications links. For example, handheld electronic devices may communicate using the WiFi® (IEEE 802.11) band at 2.4 GHz and the Bluetooth® band at 2.4 GHz.

To satisfy consumer demand for small form factor wireless devices, manufacturers are continually striving to reduce the size of components that are used in these devices. For example, manufacturers have made attempts to miniaturize the antennas used in handheld electronic devices.

A typical antenna may be fabricated by patterning a metal layer on a circuit board substrate or may be formed from a sheet of thin metal using a foil stamping process. Many devices use planar inverted-F antennas (PIFAs). Planar inverted-F antennas are formed by locating a planar resonating element above a ground plane. These techniques can be used to produce antennas that fit within the tight confines of a compact handheld device.

To provide sufficient wireless coverage over all communications bands of interest, modern handheld electronic devices sometimes contain multiple antennas. For example, a modern handheld electronic device might have one antenna for handling cellular telephone communications in cellular telephone bands and another antenna for handling data communications in a data communications band. Although the operating frequencies of the cellular telephone antenna and the data communications antenna are different, there will still generally be a tendency for undesirable electromagnetic coupling between the antennas.

This electromagnetic coupling forms an undesirable type of signal interference. Unless the antennas are sufficiently isolated from each other, simultaneous antenna operation will not be possible.

Electromagnetic isolation between two antennas can often be obtained by placing the antennas as far apart as possible within the confines of the handheld electronic device. However, conventional spatial separation arrangements such as these are not always feasible. In some designs, layout constraints prevent the use of spatial separation for reducing antenna interference.

It would therefore be desirable to be able to provide improved ways in which to isolate antennas from each other in a handheld electronic device.

SUMMARY

In accordance with an embodiment of the present invention, a handheld electronic device with wireless communications circuitry is provided. The handheld electronic device may have cellular telephone, music player, or handheld computer functionality. The wireless communications circuitry may have at least first and second antennas.

The first and second antennas may be located in close proximity to each other within the handheld electronic device. With one suitable arrangement, the first antenna is a hybrid planar-inverted-F and slot antenna and the second antenna is an L-shaped strip antenna. The first and second antennas may have respective first and second planar resonating elements. The first and second planar resonating elements may be formed on a flex circuit that is mounted to a dielectric support structure.

A rectangular ground plane element may serve as ground for the first and second antennas. The handheld electronic device may have a metal housing portion that is shorted to ground and may have a plastic cap portion that covers the first and second planar resonating elements.

The rectangular ground plane element may contain a rectangular dielectric-filled slot. The planar resonating elements may be located above the slot. The first planar resonating element may have two arms. A first of the two arms may be tuned to resonate at approximately the same frequency band as the second antenna. When the first and second antennas are operated simultaneously, the first arm serves to cancel interference from the second antenna and thereby serves as an antenna isolation element that helps to isolate the first and second antennas from each other. A second of the two arms may be configured to resonate at the same frequency as the slot portion of the first antenna to enhance the gain and bandwidth of the first antenna at that frequency.

Further features of the invention, its nature and various advantages will be more apparent from the accompanying drawings and the following detailed description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an illustrative handheld electronic device with an antenna in accordance with an embodiment of the present invention.

FIG. **2** is a schematic diagram of an illustrative handheld electronic device with an antenna in accordance with an embodiment of the present invention.

FIG. **3**A is a cross-sectional side view of an illustrative handheld electronic device with an antenna in accordance with an embodiment of the present invention.

FIG. **3**B is a partly schematic top view of an illustrative handheld electronic device containing two radio-frequency transceivers that are coupled to two associated antenna resonating elements by respective transmission lines in accordance with an embodiment of the present invention.

FIG. **4** is a perspective view of an illustrative planar inverted-F antenna (PIFA) in accordance with an embodiment of the present invention.

FIG. **5** is a cross-sectional side view of an illustrative planar inverted-F antenna of the type shown in FIG. **4** in accordance with an embodiment of the present invention.

FIG. **6** is an illustrative antenna performance graph for an antenna of the type shown in FIGS. **4** and **5** in which standing-wave-ratio (SWR) values are plotted as a function of operating frequency.

FIG. **7** is a perspective view of an illustrative planar inverted-F antenna in which a portion of the antenna's ground plane underneath the antenna's resonating element has been removed to form a slot in accordance with an embodiment of the present invention.

FIG. **8** is a top view of an illustrative slot antenna in accordance with an embodiment of the present invention.

FIG. **9** is an illustrative antenna performance graph for an antenna of the type shown in FIG. **8** in which standing-wave-ratio (SWR) values are plotted as a function of operating frequency.

FIG. **10** is a perspective view of an illustrative hybrid PIFA/slot antenna formed by combining a planar inverted-F antenna with a slot antenna in which the antenna is being fed by two coaxial cable feeds in accordance with an embodiment of the present invention.

FIG. **11** is an illustrative wireless coverage graph in which antenna standing-wave-ratio (SWR) values are plotted as a function of operating frequency for a handheld device that contains a hybrid PIFA/slot antenna and a strip antenna in accordance with an embodiment of the present invention.

FIG. **12** is a perspective view of an illustrative handheld electronic device antenna arrangement in which a first of two handheld electronic device antennas has an associated isolation element that serves to reduce interference with from a second of the two handheld electronic device antennas in accordance with an embodiment of the present invention.

FIG. **13** is a graph in which antenna isolation performance is plotted as a function of operating frequency for an unisolated antenna arrangement and an antenna arrangement with an isolation element in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

The present invention relates generally to wireless communications, and more particularly, to wireless electronic devices and antennas for wireless electronic devices.

The antennas may be small form factor antennas that exhibit wide bandwidths and large gains.

The wireless electronic devices may be portable electronic devices such as laptop computers or small portable computers of the type that are sometimes referred to as ultraportables. Portable electronic devices may also be somewhat smaller devices. Examples of smaller portable electronic devices include wrist-watch devices, pendant devices, headphone and earpiece devices, and other wearable and miniature devices.

With one suitable arrangement, the portable electronic devices are handheld electronic devices. Space is at a premium in handheld electronics devices, so high-performance compact antennas can be particularly advantageous in such devices. The use of handheld devices is therefore generally described herein as an example, although any suitable electronic device may be used with the antennas of the invention if desired.

The handheld devices may be, for example, cellular telephones, media players with wireless communications capabilities, handheld computers (also sometimes called personal digital assistants), remote controllers, global positioning system (GPS) devices, and handheld gaming devices. The handheld devices may also be hybrid devices that combine the functionality of multiple conventional devices. Examples of hybrid handheld devices include a cellular telephone that includes media player functionality, a gaming device that includes a wireless communications capability, a cellular telephone that includes game and email functions, and a handheld device that receives email, supports mobile telephone calls, and supports web browsing. These are merely illustrative examples.

An illustrative handheld electronic device in accordance with an embodiment of the present invention is shown in FIG. **1**. Device **10** may be any suitable portable or handheld electronic device.

Device **10** includes housing **12** and includes two or more antennas for handling wireless communications. Embodiments of device **10** that contain two antennas are described herein as an example.

Each of the two antennas in device **10** may handle communications over a respective communications band or group of communications bands. For example, a first of the two antennas may be used to handle cellular telephone frequency bands. A second of the two antennas may be used to handle data communications in a separate communications band. With one suitable arrangement, which is sometimes described herein as an example, the second antenna is configured to handle data communications in a communications band centered at 2.4 GHz (e.g., WiFi and/or Bluetooth frequencies). The design of the antennas helps to reduce interference and allows the two antennas to operate in relatively close proximity to each other.

Housing **12**, which is sometimes referred to as a case, may be formed of any suitable materials including, plastic, glass, ceramics, metal, or other suitable materials, or a combination of these materials. In some situations, case **12** may be formed from a dielectric or other low-conductivity material, so that the operation of conductive antenna elements that are located in proximity to case **12** is not disrupted. In other situations, case **12** may be formed from metal elements. In scenarios in which case **12** is formed from metal elements, one or more of the metal elements may be used as part of the antennas in device **10**. For example, metal portions of case **12** may be shorted to an internal ground plane in device **10** to create a larger ground plane element for that device **10**.

Handheld electronic device **10** may have input-output devices such as a display screen **16**, buttons such as button **23**, user input control devices **18** such as button **19**, and input-output components such as port **20** and input-output jack **21**. Display screen **16** may be, for example, a liquid crystal display (LCD), an organic light-emitting diode (OLED) display, a plasma display, or multiple displays that use one or more different display technologies. As shown in the example of FIG. **1**, display screens such as display screen **16** can be mounted on front face **22** of handheld electronic device **10**. If desired, displays such as display **16** can be mounted on the rear face of handheld electronic device **10**, on a side of device **10**, on a flip-up portion of device **10** that is attached to a main body portion of device **10** by a hinge (for example), or using any other suitable mounting arrangement.

A user of handheld device **10** may supply input commands using user input interface **18**. User input interface **18** may include buttons (e.g., alphanumeric keys, power on-off, power-on, power-off, and other specialized buttons, etc.), a touch pad, pointing stick, or other cursor control device, a touch screen (e.g., a touch screen implemented as part of screen **16**), or any other suitable interface for controlling device **10**. Although shown schematically as being formed on the top face **22** of handheld electronic device **10** in the example of FIG. **1**, user input interface **18** may generally be formed on any suitable portion of handheld electronic device **10**. For example, a button such as button **23** (which may be considered to be part of input interface **18**) or other user interface control may be formed on the side of handheld electronic device **10**. Buttons and other user interface controls can also be located on the top face, rear face, or other portion of device **10**. If desired, device **10** can be controlled remotely (e.g., using an infrared remote control, a radio-frequency remote control such as a Bluetooth remote control, etc.).

Handheld device **10** may have ports such as bus connector **20** and jack **21** that allow device **10** to interface with external components. Typical ports include power jacks to recharge a battery within device **10** or to operate device **10** from a direct current (DC) power supply, data ports to exchange data with external components such as a personal computer or peripheral, audio-visual jacks to drive headphones, a monitor, or other external audio-video equipment, etc. The functions of some or all of these devices and the internal circuitry of handheld electronic device **10** can be controlled using input interface **18**.

Components such as display **16** and user input interface **18** may cover most of the available surface area on the front face **22** of device **10** (as shown in the example of FIG. **1**) or may occupy only a small portion of the front face **22**. Because electronic components such as display **16** often contain large amounts of metal (e.g., as radio-frequency shielding), the location of these components relative to the antenna elements in device **10** should generally be taken into consideration. Suitably chosen locations for the antenna elements and electronic components of the device will allow the antennas of handheld electronic device **10** to function properly without being disrupted by the electronic components.

With one suitable arrangement, the antennas of device **10** are located in the lower end of device **10**, in the proximity of port **20**. An advantage of locating antennas in the lower portion of housing **12** and device **10** is that this places the antennas away from the user's head when the device **10** is held to the head (e.g., when talking into a microphone and listening to a speaker in the handheld device as with a cellular telephone). This reduces the amount of radio-frequency radiation that is emitted in the vicinity of the user and minimizes proximity effects. However, locating both of the antennas at the same end of device **10** raises the possibility of undesirable interference between the antennas when the antennas are in simultaneous operation. To improve isolation to a satisfactory level, at least one of the antennas may be provided with an isolation element that reduces electromagnetic coupling between the antennas. By reducing electromagnetic coupling in this way, the antennas may be placed in relatively close proximity to each other without hindering the ability of the antennas to be operated simultaneously.

A schematic diagram of an embodiment of an illustrative handheld electronic device is shown in FIG. **2**. Handheld device **10** may be a mobile telephone, a mobile telephone with media player capabilities, a handheld computer, a remote control, a game player, a global positioning system (GPS) device, a combination of such devices, or any other suitable portable electronic device.

As shown in FIG. **2**, handheld device **10** may include storage **34**. Storage **34** may include one or more different types of storage such as hard disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory), volatile memory (e.g., battery-based static or dynamic random-access-memory), etc.

Processing circuitry **36** may be used to control the operation of device **10**. Processing circuitry **36** may be based on a processor such as a microprocessor and other suitable integrated circuits. With one suitable arrangement, processing circuitry **36** and storage **34** are used to run software on device **10**, such as internet browsing applications, voice-over-internet-protocol (VOIP) telephone call applications, email applications, media playback applications, operating system functions, etc. Processing circuitry **36** and storage **34** may be used in implementing suitable communications protocols. Communications protocols that may be implemented using processing circuitry **36** and storage **34** include internet protocols, wireless local area network protocols (e.g., IEEE 802.11 protocols—sometimes referred to as WiFi®, protocols for other short-range wireless communications links such as the Bluetooth® protocol, etc.).

Input-output devices **38** may be used to allow data to be supplied to device **10** and to allow data to be provided from device **10** to external devices. Display screen **16** and user input interface **18** of FIG. **1** are examples of input-output devices **38**.

Input-output devices **38** can include user input-output devices **40** such as buttons, touch screens, joysticks, click wheels, scrolling wheels, touch pads, key pads, keyboards, microphones, cameras, etc. A user can control the operation of device **10** by supplying commands through user input devices **40**. Display and audio devices **42** may include liquid-crystal display (LCD) screens, light-emitting diodes (LEDs), and other components that present visual information and status data. Display and audio devices **42** may also include audio equipment such as speakers and other devices for creating sound. Display and audio devices **42** may contain audio-video interface equipment such as jacks and other connectors for external headphones and monitors.

Wireless communications devices **44** may include communications circuitry such as radio-frequency (RF) transceiver circuitry formed from one or more integrated circuits, power amplifier circuitry, passive RF components, two or more antennas, and other circuitry for handling RF wireless signals. Wireless signals can also be sent using light (e.g., using infrared communications).

Device **10** can communicate with external devices such as accessories **46** and computing equipment **48**, as shown by paths **50**. Paths **50** may include wired and wireless paths. Accessories **46** may include headphones (e.g., a wireless cellular headset or audio headphones) and audio-video equipment (e.g., wireless speakers, a game controller, or other equipment that receives and plays audio and video content).

Computing equipment **48** may be any suitable computer. With one suitable arrangement, computing equipment **48** is a computer that has an associated wireless access point (router) or an internal or external wireless card that establishes a wireless connection with device **10**. The computer may be a server (e.g., an internet server), a local area network computer with or without internet access, a user's own personal computer, a peer device (e.g., another handheld electronic device **10**), or any other suitable computing equipment.

The antennas and wireless communications devices of device **10** may support communications over any suitable wireless communications bands. For example, wireless communications devices **44** may be used to cover communications frequency bands such as the cellular telephone bands at 850 MHz, 900 MHz, 1800 MHz, and 1900 MHz, data service bands such as the 3G data communications band at 2170 MHz band (commonly referred to as UMTS or Universal Mobile Telecommunications System), the WiFi® (IEEE 802.11) bands at 2.4 GHz and 5.0 GHz, the Bluetooth® band at 2.4 GHz, and the global positioning system (GPS) band at 1550 MHz. These are merely illustrative communications bands over which devices **44** may operate. Additional local and remote communications bands are expected to be deployed in the future as new wireless services are made available. Wireless devices **44** may be configured to operate over any suitable band or bands to cover any existing or new services of interest. If desired, three or more antennas may be provided in wireless devices **44** to allow coverage of more bands, although the use of two antennas is primarily described herein as an example.

A cross-sectional view of an illustrative handheld electronic device is shown in FIG. **3**A. In the example of FIG. **3**A, device **10** has a housing that is formed of a conductive portion **12-1** and a plastic portion **12-2**. Conductive portion **12-1** may be any suitable conductor. With one suitable arrangement, case portion **12-1** is formed from metals such as stamped 304 stainless steel. Stainless steel has a high conductivity and can be polished to a high-gloss finish so that it has an attractive appearance. If desired, other metals can be used for case portion **12-1** such as aluminum, magnesium, titanium, alloys of these metals and other metals, etc.

Housing portion **12-2** may be formed from a dielectric. An advantage of using dielectric for housing portion **12-2** is that this allows antenna resonating elements **54-1**A and **54-1**B of antennas **54** in device **10** to operate without interference from the metal sidewalls of housing **12**. With one suitable arrangement, housing portion **12-2** is a plastic cap formed from a plastic based on acrylonitrile-butadiene-styrene copolymers (sometimes referred to as ABS plastic). These are merely illustrative housing materials for device **10**. For example, the housing of device **10** may be formed substantially from plastic or other dielectrics, substantially from metal or other conductors, or from any other suitable materials or combinations of materials.

Components such as components **52** may be mounted on one or more circuit boards in device **10**. Typical components include integrated circuits, LCD screens, and user input interface buttons. Device **10** also typically includes a battery, which may be mounted along the rear face of housing **12** (as an example). Transceiver circuits **52**A and **52**B may also be mounted to one or more circuit boards in device **10**. If desired, there may be more transceivers. In a configuration for device **10** in which there are two antennas and two transceivers, each transceiver may be used to transmit radio-frequency signals through a respective antenna and may be used to receive radio-frequency signals through a respective antenna. For example, transceiver **52**A may be used to transmit and receive cellular telephone radio-frequency signals and transceiver **52**B may be used to transmit signals in a communications band such as the 3G data communications band at 2170 MHz band (commonly referred to as UMTS or Universal Mobile Telecommunications System), the WiFi® (IEEE 802.11) bands at 2.4 GHz and 5.0 GHz, the Bluetooth® band at 2.4 GHz, or the global positioning system (GPS) band at 1550 MHz.

The circuit board(s) in device **10** may be formed from any suitable materials. With one illustrative arrangement, device **10** is provided with a multilayer printed circuit board. At least one of the layers may have large uninterrupted planar regions of conductor that form a ground plane such as ground plane **54-2**. In a typical scenario, ground plane **54-2** is a rectangle that conforms to the generally rectangular shape of housing **12** and device **10** and matches the rectangular lateral dimensions of housing **12**. Ground plane **54-2** may, if desired, be electrically connected to conductive housing portion **12-1**.

Suitable circuit board materials for the multilayer printed circuit board include paper impregnated with phonolic resin, resins reinforced with glass fibers such as fiberglass mat impregnated with epoxy resin (sometimes referred to as FR-4), plastics, polytetrafluoroethylene, polystyrene, polyimide, and ceramics. Circuit boards fabricated from materials such as FR-4 are commonly available, are not cost-prohibitive, and can be fabricated with multiple layers of metal (e.g., four layers). So-called flex circuits, which are formed using flexible circuit board materials such as polyimide, may also be used in device **10**. For example, flex circuits may be used to form the antenna resonating elements for antennas **54**.

As shown in the illustrative configuration of FIG. **3**A, ground plane element **54-2** and antenna resonating element **54-1**A may form a first antenna for device **10**. Ground plane element **54-2** and antenna resonating element **54-1**B may form a second antenna for device **10**. If desired, other antennas can be provided for device **10** in addition to these two antennas. Such additional antennas may, if desired, be configured to provide additional gain for an overlapping frequency band of interest (i.e., a band at which one of these antennas **54** is operating) or may be used to provide coverage in a different frequency band of interest (i.e., a band outside of the range of antennas **54**).

Any suitable conductive materials may be used to form ground plane element **54-2** and resonating elements **54-1**A and **54-1**B in the antennas. Examples of suitable conductive materials for the antennas include metals, such as copper, brass, silver, and gold. Conductors other than metals may also be used, if desired. The conductive elements in antennas **54** are typically thin (e.g., about 0.2 mm).

Transceiver circuits **52**A and **52**B (i.e., transceiver circuitry **44** of FIG. **2**) may be provided in the form of one or more integrated circuits and associated discrete components (e.g., filtering components). These transceiver circuits may include one or more transmitter integrated circuits, one or more receiver integrated circuits, switching circuitry, amplifiers, etc. Transceiver circuits **52**A and **52**B may operate simultaneously (e.g., one can transmit while the other receives, both can transmit at the same time, or both can receive simultaneously).

Each transceiver may have an associated coaxial cable or other transmission line over which transmitted and received radio frequency signals are conveyed. As shown in the example of FIG. **3**A, transmission line **56**A (e.g., a coaxial cable) may be used to interconnect transceiver **52**A and antenna resonating element **54-1**A and transmission line **56**B (e.g., a coaxial cable) may be used to interconnect transceiver **52**B and antenna resonating element **54-1**B. With this type of configuration, transceiver **52**B may handle WiFi transmissions over an antenna formed from resonating element **54-1**B and ground plane **54-2**, while transceiver **52**A may handle cellular telephone transmission over an antenna formed from resonating element **54-1**A and ground plane **54-2**.

A top view of an illustrative device **10** in accordance with an embodiment of the present invention is shown in FIG. **3**B. As shown in FIG. **3**B, transceiver circuitry such as transceiver **52**A and transceiver **52**B may be interconnected with antenna resonating elements **54-1**A and **54-1**B over respective transmission lines **56**A and **56**B. Ground plane **54-2** may have a substantially rectangular shape (i.e., the lateral dimensions of ground plane **54-2** may match those of device **10**). Ground plane **54-2** may be formed from one or more printed circuit board conductors, conductive housing portions (e.g., housing portion **12-1** of FIG. **3**A), or any other suitable conductive structure.

Antenna resonating elements **54-1**A and **54-1**B and ground plane **54-2** may be formed in any suitable shapes. With one illustrative arrangement, one of antennas **54** (i.e., the antenna formed from resonating element **54-1**A) is based at least partly on a planar inverted-F antenna (PIFA) structure and the other antenna (i.e., the antenna formed from resonating element **54-1**B) is based on a planar strip configuration.

Although this embodiment may be described herein as an example, any other suitable shapes may be used for resonating element **54-1**A and **54-1**B if desired.

An illustrative PIFA structure that may be used in device **10** is shown in FIG. **4**. As shown in FIG. **4**, PIFA structure **54** may have a ground plane portion **54-2** and a planar resonating element portion **54-1**. Antennas are fed using positive signals and ground signals. The portion of an antenna to which the positive signal is provided is sometimes referred to as the antenna's positive terminal or feed terminal. This terminal is also sometimes referred to as the signal terminal or the center-conductor terminal of the antenna. The portion of an antenna to which the ground signal is provided may be referred to as the antenna's ground, the antenna's ground terminal, the antenna's ground plane, etc. In antenna **54** of FIG. **4**, feed conductor **58** is used to route positive antenna signals from signal terminal **60** into antenna resonating element **54-1**. Ground terminal **62** is shorted to ground plane **54-2**, which forms the antenna's ground.

The dimensions of the ground plane in a PIFA antenna such as antenna **54** of FIG. **4** are generally sized to conform to the maximum size allowed by housing **12** of device **10**. Antenna ground plane **54-2** may be rectangular in shape having width W in lateral dimension **68** and length L in lateral dimension **66**. The length of antenna **54** in dimension **66** affects its frequency of operation. Dimensions **68** and **66** are sometimes referred to as horizontal dimensions. Resonating element **54-1** is typically spaced several millimeters from ground plane **54-2** along vertical dimension **64**. The size of antenna **54** in dimension **64** is sometimes referred to as height H of antenna **54**.

A cross-sectional view of PIFA antenna **54** of FIG. **4** is shown in FIG. **5**. As shown in FIG. **5**, radio-frequency signals may be fed to antenna **54** (when transmitting) and may be received from antenna **54** (when receiving) using signal terminal **60** and ground terminal **62**. In a typical arrangement, a coaxial conductor or other transmission line has its center conductor electrically connected to point **60** and its ground conductor electrically connected to point **62**.

A graph of the expected performance of an antenna of the type represented by illustrative antenna **54** of FIGS. **4** and **5** is shown in FIG. **6**. Expected standing wave ratio (SWR) values are plotted as a function of frequency. The performance of antenna **54** of FIGS. **4** and **5** is given by solid line **63**. As shown, there is a reduced SWR value at frequency f_1, indicating that the antenna performs well in the frequency band centered at frequency f_1. PIFA antenna **54** also operates at harmonic frequencies such as frequency f_2. Frequency f_2 represents the second harmonic of PIFA antenna **54** (i.e., $f_2=2f_1$). The dimensions of antenna **54** may be selected so that frequencies f_1 and f_2 are aligned with communication bands of interest. The frequency f_1 (and harmonic frequency $2f_1$) are related to the length L of antenna **54** in dimension **66** (L is approximately equal to one quarter of a wavelength at frequency f_1).

The height H of antenna **54** of FIGS. **4** and **5** in dimension **64** is limited by the amount of near-field coupling between resonating element **54-1**A and ground plane **54-2**. For a specified antenna bandwidth and gain, it is not possible to reduced the height H without adversely affecting performance. All other variables being equal, reducing height H will cause the bandwidth and gain of antenna **54** to be reduced.

As shown in FIG. **7**, the minimum vertical dimension of the PIFA antenna can be reduced while still satisfying minimum bandwidth and gain constraints by introducing a dielectric region **70** in the area under antenna resonating element **54-1**A. The dielectric region **70** may be filled with air, plastic, or any other suitable dielectric and represents a cut-away or removed portion of ground plane **54-2**. Removed or empty region **70** may be formed from one or more holes in ground plane **54-2**. These holes may be square, circular, oval, polygonal, etc. and may extend though adjacent conductive structures in the vicinity of ground plane **54-2**. With one suitable arrangement, which is shown in FIG. **7**, the removed region **70** is rectangular and forms a slot. The slot may be any suitable size. For example, the slot may be slightly smaller than the outermost rectangular outline of resonating elements **54-1**A and **54-2** as viewed from the top view orientation of FIG. **3**B. Typical resonating element lateral dimensions are on the order of 0.5 cm to 10 cm.

The presence of slot **70** reduces near-field electromagnetic coupling between resonating element **54-1**A and ground plane **54-2** and allows height H in vertical dimension **64** to be made smaller than would otherwise be possible while satisfying a given set of bandwidth and gain constraints. For example, height H may be in the range of 1-5 mm, may be in the range of 2-5 mm, may be in the range of 2-4 mm, may be in the range of 1-3 mm, may be in the range of 1-4 mm, may be in the range of 1-10 mm, may be lower than 10 mm, may be lower than 4 mm, may be lower than 3 mm, may be lower than 2 mm, or may be in any other suitable range of vertical displacements above ground plane element **54-2**.

If desired, the portion of ground plane **54-2** that contains slot **70** may be used to form a slot antenna. The slot antenna structure may be used at the same time as the PIFA structure to form a hybrid antenna **54**. By operating antenna **54** so that it exhibits both PIFA operating characteristics and slot antenna operating characteristics, antenna performance can be improved.

A top view of an illustrative slot antenna is shown in FIG. **8**. Antenna **72** of FIG. **8** is typically thin in the dimension into the page (i.e., antenna **72** is planar with its plane lying in the page). Slot **70** may be formed in the center of antenna **72**. A coaxial cable such as cable **56**A or other transmission line path may be used to feed antenna **72**. In the example of FIG. **8**, antenna **72** is fed so that center conductor **82** of coaxial cable **56**A is connected to signal terminal **80** (i.e., the positive or feed terminal of antenna **72**) and the outer braid of coaxial cable **56**A, which forms the ground conductor for cable **56**A, is connected to ground terminal **78**.

When antenna **72** is fed using the arrangement of FIG. **8**, the antenna's performance is given by the graph of FIG. **9**. As shown in FIG. **9**, antenna **72** operates in a frequency band that is centered about center frequency f_2. The center frequency f_2 is determined by the dimensions of slot **70**. Slot **70** has an inner perimeter P that is equal to two times dimension X plus two times dimension Y (i.e., P=2X+2Y). At center frequency f_2, perimeter P is equal to one wavelength.

Because the center frequency f_2 can be tuned by proper selection of perimeter P, the slot antenna of FIG. **8** can be configured so that frequency f_2 of the graph in FIG. **9** coincides with frequency f_2 of the graph in FIG. **6**. In an antenna design in which slot **70** is combined with a PIFA structure, the presence of slot **70** increases the gain of the antenna at frequency f_2. In the vicinity of frequency f_2, the increase in performance from using slot **70** results in the antenna performance plot given by dotted line **79** in FIG. **6**.

The position of terminals **80** and **78** may be selected for impedance matching. If desired, terminals such as terminals **84** and **86**, which extend around one of the corners of slot **70** may be used to feed antenna **72**. In this situation, the distance between terminals **84** and **86** may be chosen to properly adjust the impedance of antenna **72**. In the illustrative arrangement of FIG. **8**, terminals **84** and **86** are shown as being respectively configured as a slot antenna ground terminal and a slot antenna signal terminal, as an example. If desired, terminal **84** could be used as a ground terminal and terminal **86** could be used as a signal terminal. Slot **70** is typically air-filled, but may, in general, by filled with any suitable dielectric.

By using slot **70** in combination with a PIFA-type resonating element such as resonating element **54-1**, a hybrid PIFA/slot antenna is formed. Handheld electronic device **10** may, if desired, have a PIFA/slot hybrid antenna of this type (e.g., for cellular telephone communications) and a strip antenna (e.g., for WiFi/Bluetooth communications).

An illustrative configuration in which the hybrid PIFA/slot antenna formed by resonating element **54-1**A, slot **70**, and ground plane **54-2** is fed using two coaxial cables (or other transmission lines) is shown in FIG. **10**. When the antenna is fed as shown in FIG. **10**, both the PIFA and slot antenna portions of the antenna are active. As a result, antenna **54** of FIG. **10** operates in a hybrid PIFA/slot mode. Coaxial cables **56**A**-1** and **56**A**-2** have inner conductors **82-1** and **82-2**, respectively. Coaxial cables **56**A**-1** and **56**A**-2** also each have a conductive outer braid ground conductor. The outer braid conductor of coaxial cable **56**A**-1** is electrically shorted to ground plane **54-2** at ground terminal **88**. The ground portion of cable **56**A**-2** is shorted to ground plane **54-2** at ground terminal **92**. The signal connections from coaxial cables **56**A**-1** and **56**A**-2** are made at signal terminals **90** and **94**, respectively.

With the arrangement of FIG. **10**, two separate sets of antenna terminals are used. Coaxial cable **56**A**-1** feeds the PIFA portion of the hybrid PIFA/slot antenna using ground terminal **88** and signal terminal **90** and coaxial cable **56**A**-2** feeds the slot antenna portion of the hybrid PIFA/slot antenna using ground terminal **92** and signal terminal **94**. Each set of antenna terminals therefore operates as a separate feed for the hybrid PIFA/slot antenna. Signal terminal **90** and ground terminal **88** serve as antenna terminals for the PIFA portion of the antenna, whereas signal terminal **94** and ground terminal **92** serve as antenna feed points for the slot portion of antenna **54**. These two separate antenna feeds allow the antenna to function simultaneously using both its PIFA and its slot characteristics. If desired, the orientation of the feeds can be changed. For example, coaxial cable **56**A**-2** may be connected to slot **70** using point **94** as a ground terminal and point **92** as a signal terminal or using ground and signal terminals located at other points along the periphery of slot **70**.

When multiple transmission lines such as transmission lines **56**A**-1** and **56-2** are used for the hybrid PIFA/slot antenna, each transmission line may be associated with a respective transceiver circuit (e.g., two corresponding transceiver circuits such as transceiver circuit **52**A of FIGS. **3**A and **3**B).

In operation in handheld device **10**, a hybrid PIFA/slot antenna formed from resonating element **54-1**A of FIG. **3**B and a corresponding slot that is located beneath element **54-1**A in ground plane **54-2** can be used to cover the GSM cellular telephone bands at 850 and 900 MHz and at 1800 and 1900 MHz (or other suitable frequency bands), whereas a strip antenna (or other suitable antenna structure) can be used to cover an additional band centered at frequency f_n (or another suitable frequency band or bands). By adjusting the size of the strip antenna or other antenna structure formed from resonating element **54-1**B, the frequency f_n may be controlled so that it coincides with any suitable frequency band of interest (e.g., 2.4 GHz for Bluetooth/WiFi, 2170 MHz for UMTS, or 1550 MHz for GPS).

A graph showing the wireless performance of device **10** when using two antennas (e.g., a hybrid PIFA/slot antenna formed from resonating element **54-1**A and a corresponding slot and an antenna formed from resonating element **54-2**) is shown in FIG. **11**. In the example of FIG. **11**, the PIFA operating characteristics of the hybrid PIFA/slot antenna are used to cover the 850/900 MHz and the 1800/1900 MHz GSM cellular telephone bands, the slot antenna operating characteristics of the hybrid PIFA/slot antenna are used to provide additional gain and bandwidth in the 1800/1900 MHz range, and the antenna formed from resonating element **54-1**B is used to cover the frequency band centered at f_n (e.g., 2.4 GHz for Bluetooth/WiFi, 2170 MHz for UMTS, or 1550 MHz for GPS). This arrangement provides coverage for four cellular telephone bands and a data band.

If desired, the hybrid PIFA/slot antenna formed from resonating element **54-1**A and slot **70** may be fed using a single coaxial cable or other such transmission line. An illustrative configuration in which a single transmission line is used to simultaneously feed both the PIFA portion and the slot portion of the hybrid PIFA/slot antenna and in which a strip antenna formed from resonating element **54-1**B is used to provide additional frequency coverage for device **10** is shown in FIG. **12**. Ground plane **54-2** may be formed from metal (as an example). Edges **96** of ground plane **54-2** may be formed by bending the metal of ground plane **54-2** upward. When inserted into housing **12** (FIG. **3**A), edges **96** may rest within the sidewalls of metal housing portion **12-1**. If desired, ground plane **54-2** may be formed using one or more metal layers in a printed circuit board, metal foil, portions of housing **12**, or other suitable conductive structures.

In the embodiment of FIG. **12**, resonating element **54-1**B has an L-shaped conductive strip formed from conductive branch **122** and conductive branch **120**. Branches **120** and **122** may be formed from metal that is supported by dielectric support structure **102**. With one suitable arrangement, the resonating element structures of FIG. **12** are formed as part of a patterned flex circuit that is attached to support structure **102** (e.g., by adhesive).

Coaxial cable **56**B or other suitable transmission line has a ground conductor connected to ground terminal **132** and a signal conductor connected to signal terminal **124**. Any suitable mechanism may be used for attaching the transmission line to the antenna. In the example of FIG. **12**, the outer braid ground conductor of coaxial cable **56**B is connected to ground terminal **132** using metal tab **130**. Metal tab **130** may be shorted to housing portion **12-1** (e.g., using conductive adhesive). Transmission line connection structure **126** may be, for example, a mini UFL coaxial connector. The ground of connector **126** may be shorted to terminal **132** and the center conductor of connector **126** may be shorted to conductive path **124**.

When feeding antenna **54-1**B, terminal **132** may be considered to form the antenna's ground terminal and the center conductor of connector **126** and/or conductive path **124** may be considered to form the antenna's signal terminal. The location along dimension **128** at which conductive path **124** meets conductive strip **120** can be adjusted for impedance matching.

Planar antenna resonating element **54-1**A of the hybrid PIFA/slot antenna of FIG. **12** may have an F-shaped structure with shorter arm **98** and longer arm **100**. The lengths of arms **98** and **100** and the dimensions of other structures such as slot **70** and ground plane **54-2** may be adjusted to tune the frequency coverage and antenna isolation properties of device **10**. For example, length L of ground plane **54-2** may be configured so that the PIFA portion of the hybrid PIFA/slot antenna formed with resonating element **54-1**A resonates at the 850/900 MHz GSM bands, thereby providing coverage at frequency f_1 of FIG. **11**. The length of arm **100** may be selected to resonate at the 1800/1900 MHz bands, thereby helping the PIFA/slot antenna to provide coverage at frequency f_2 of FIG. **11**. The perimeter of slot **70** may be configured to resonate at the 1800/1900 MHz bands, thereby reinforcing the resonance of arm **100** and further helping the PIFA/slot antenna to provide coverage at frequency f_2 of FIG. **11** (i.e., by improving performance from the solid line **63** to the dotted line **79** in the vicinity of frequency f_2, as shown in FIG. **6**).

Arm **98** can serve as an isolation element that reduces interference between the hybrid PIFA/slot antenna formed from resonating element **54-1**A and the L-shaped strip antenna formed from resonating element **54-1**B. The dimensions of arm **98** can be configured to introduce an isolation maximum at a desired frequency, which is not present without the arm. It is believed that configuring the dimensions of arm **98** allows manipulation of the currents induced on the ground plane **54-2** from resonating element **54-1**A. This manipulation can minimize induced currents around the signal and ground areas of resonating element **54-1**B. Minimizing these currents in turn reduces the signal coupling between the two antenna feeds. With this arrangement, arm **98** can be configured to resonate at a frequency that minimizes currents induced by arm **100** at the feed of the antenna formed from resonating element **54-1**B (i.e., in the vicinity of paths **122** and **124**).

Additionally, arm **98** can act as a radiating arm for element **54-1**A. Its resonance can add to the bandwidth of element **54-1**A and can improve in-band efficiency, even though its resonance may be different than that defined by slot **70** and arm **100**. Typically an increase in bandwidth of radiating element **51-1**A that reduces its frequency separation from element **51-1**B would be detrimental to isolation. However, extra isolation afforded by arm **98** removes this negative effect and, moreover, provides significant improvement with respect to the isolation between elements **54-1**A and **54-1**B without arm **98**.

The impact that use of an isolating element such as arm **98** has on antenna isolation performance in device **10** is shown in the graph of FIG. **13**. The amount of signal appearing on one antenna as a result of signals on the other antenna (the S_{21} value for the antennas) is plotted as a function of frequency. The amount of isolation that is required for device **10** depends on the type of circuitry used in the transceivers, the types of data rates that are desired, the amount of external interference that is anticipated, the frequency band of operation, the types of applications being run on device **10**, etc. In general, isolation levels of 7 dB or less are considered poor and isolation levels of 20-25 dB are considered good. An illustrative desired minimum isolation level for a handheld electronic device is depicted by solid line **142**. As this example illustrates, there may be a frequency dependence to the amount of antenna interference that a given design may tolerate. Isolation requirements may (as an example) be less for operation in the vicinity of frequency f_2 than when operating at frequencies f_1 and f_n.

In the example of FIG. **13**, the strip antenna has been configured for operation at 2.4 GHz (e.g., for WiFi/Bluetooth). Dashed-and-dotted line **144** represents the isolation performance of the antennas when no isolation element such as arm **98** is used. As shown by line **144**, isolation performance for this type of antenna arrangement is poor, because isolation at 2.4 GHz is less than 7 dB. In contrast, dashed line **140** depicts the isolation performance of antennas of the type shown in FIG. **12** in which an isolation element such as arm **98** is used. When arm **98** is used, isolation performance is improved. As shown by the position of line **140**, the isolation performance of the illustrative antennas of FIG. **12** meets or exceeds the minimum requirements set by line **142**.

As shown in FIG. **12**, arms **98** and **100** of resonating element **54-1**A and resonating element **54-1**B may be mounted on support structure **102**. Support structure **102** may be formed from plastic (e.g., ABS plastic) or other suitable dielectric. The surfaces of structure **102** may be flat or curved. The resonating elements **54-1**A and **54-1**B may be formed directly on support structure **102** or may be formed on a separate structure such as a flex circuit substrate that is attached to support structure **102** (as examples).

Resonating elements **54-1**A and **54-**B may be formed by any suitable antenna fabrication technique such as metal stamping, cutting, etching, or milling of conductive tape or other flexible structures, etching metal that has been sputter-deposited on plastic or other suitable substrates, printing from a conducive slurry (e.g., by screen printing techniques), patterning metal such as copper that makes up part of a flex circuit substrate that is attached to support **102** by adhesive, screws, or other suitable fastening mechanisms, etc.

A conductive path such as conductive strip **104** may be used to electrically connect the resonating element **54-1**A to ground plane **54-2** at terminal **106**. A screw or other fastener at terminal **106** may be used to electrically and mechanically connect strip **104** (and therefore resonating element **54-1**A) to edge **96** of ground plane **54-2**. Conductive structures such as strip **104** and other such structures in the antennas may also be electrically connected to each other using conductive adhesive.

A coaxial cable such as cable **56**A or other transmission line may be connected to the hybrid PIFA/slot antenna to transmit and receive radio-frequency signals. The coaxial cable or other transmission line may be connected to the structures of the hybrid PIFA/slot antenna using any suitable electrical and mechanical attachment mechanism. As shown in the illustrative arrangement of FIG. **12**, mini UFL coaxial connector **110** may be used to connect coaxial cable **56**A or other transmission lines to antenna conductor **112**. A center conductor of the coaxial cable or other transmission line is connected to center connector **108** of connector **110**. An outer braid ground conductor of the coaxial cable is electrically connected to ground plane **54-2** via connector **110** at point **115** (and, if desired, may be shorted to ground plane **54-2** at other attachment points upstream of connector **110**).

Conductor **108** may be electrically connected to antenna conductor **112**. Conductor **112** may be formed from a conductive element such as a strip of metal formed on a sidewall surface of support structure **102**. Conductor **112** may be directly electrically connected to resonating element **54-1**A (e.g., at portion **116**) or may be electrically connected to resonating element **54-1**A through tuning capacitor **114** or other suitable electrical components. The size of tuning capacitor **114** can be selected to tune antenna **54** and ensure that antenna **54** covers the frequency bands of interest for device **10**.

Slot **70** may lie beneath resonating element **54-1**A of FIG. **12**. The signal from center conductor **108** may be routed to point **106** on ground plane **54-2** in the vicinity of slot **70** using a conductive path formed from antenna conductor **112**, optional capacitor **114** or other such tuning components, antenna conductor **117**, and antenna conductor **104**.

The configuration of FIG. **12** allows a single coaxial cable or other transmission line path to simultaneously feed both the PIFA portion and the slot portion of the hybrid PIFA/slot antenna.

Grounding point **115** functions as the ground terminal for the slot antenna portion of the hybrid PIFA/slot antenna that is formed by slot **70** in ground plane **54-2**. Point **106** serves as the signal terminal for the slot antenna portion of the hybrid PIFA/slot antenna. Signals are fed to point **106** via the path formed by conductive path **112**, tuning element **114**, path **117**, and path **104**.

For the PIFA portion of the hybrid PIFA/slot antenna, point **115** serves as antenna ground. Center conductor **108** and its attachment point to conductor **112** serve as the signal terminal for the PIFA. Conductor **112** serves as a feed conductor and feeds signals from signal terminal **108** to PIFA resonating element **54-1**.

In operation, both the PIFA portion and slot antenna portion of the hybrid PIFA/slot antenna contribute to the performance of the hybrid PIFA/slot antenna.

The PIFA functions of the hybrid PIFA/slot antenna are obtained by using point **115** as the PIFA ground terminal (as with terminal **62** of FIG. **7**), using point **108** at which the coaxial center conductor connects to conductive structure **112** as the PIFA signal terminal (as with terminal **60** of FIG. **7**), and using conductive structure **112** as the PIFA feed conductor (as with feed conductor **58** of FIG. **7**). During operation, antenna conductor **112** serves to route radio-frequency signals from terminal **108** to resonating element **54-1**A in the same way that conductor **58** routes radio-frequency signal from terminal **60** to resonating element **54-1**A in FIGS. **4** and **5**, whereas conductive line **104** serves to terminate the resonating element **54-1** to ground plane **54-2**, as with grounding portion **61** of FIGS. **4** and **5**.

The slot antenna functions of the hybrid PIFA/slot antenna are obtained by using grounding point **115** as the slot antenna ground terminal (as with terminal **86** of FIG. **8**), using the conductive path formed of antenna conductor **112**, tuning element **114**, antenna conductor **117**, and antenna conductor **104** as conductor **82** of FIG. **8** or conductor **82-2** of FIG. **10**, and by using terminal **106** as the slot antenna signal terminal (as with terminal **84** of FIG. **8**).

The illustrative configuration of FIG. **10** demonstrates how slot antenna ground terminal **92** and PIFA antenna ground terminal **88** may be formed at separate locations on ground plane **54-2**. In the configuration of FIG. **12**, a single coaxial cable may be used to feed both the PIFA portion of the antenna and the slot portion of the hybrid PIFA/slot antenna. This is because terminal **115** serves as both a PIFA ground terminal for the PIFA portion of the hybrid antenna and a slot antenna ground terminal for the slot antenna portion of the hybrid antenna. Because the ground terminals of the PIFA and slot antenna portions of the hybrid antenna are provided by a common ground terminal structure and because conductive paths **112**, **117**, and **104** serve to distribute radio-frequency signals to and from the resonating element **54-1**A and ground plane **54-2** as needed for PIFA and slot antenna operations, a single transmission line (e.g., coaxial conductor **56**) may be used to send and receive radio-frequency signals that are transmitted and received using both the PIFA and slot portions of the hybrid PIFA/slot antenna.

If desired, other antenna configurations may be used that support hybrid PIFA/slot operation. For example, the radio-frequency tuning capabilities of tuning capacitor **114** may be provided by a network of other suitable tuning components, such as one or more inductors, one or more resistors, direct shorting metal strip(s), capacitors, or combinations of such components. One or more tuning networks may also be connected to the hybrid antenna at different locations in the antenna structure. These configurations may be used with single-feed and multiple-feed transmission line arrangements.

Moreover, the location of the signal terminal and ground terminal in the hybrid PIFA/slot antenna may be different from that shown in FIG. **12**. For example, terminals **115**/**108** and terminal **106** can be moved relative to the locations shown in FIG. **12**, provided that the connecting conductors **112**, **117**, and **104** are suitably modified.

The PIFA portion of the hybrid PIFA/slot antenna can be provided using a substantially F-shaped conductive element having one or more arms such as arms **98** and **100** of FIG. **12** or using other arrangements (e.g., arms that are straight, serpentine, curved, have 90° bends, have 180° bends, etc.). The strip antenna formed with resonating element **54-1**B can also be formed from conductors of other shapes. Use of different shapes for the arms or other portions of resonating elements **54-1**A and **54-1**B helps antenna designers to tailor the frequency response of antenna **54** to its desired frequencies of operation and maximize isolation. The sizes of the structures in resonating elements **54-1**A and **54-1**B can be adjusted as needed (e.g., to increase or decrease gain and/or bandwidth for a particular operating band, to improve isolation at a particular frequency, etc.).

The foregoing is merely illustrative of the principles of this invention and various modifications can be made by those skilled in the art without departing from the scope and spirit of the invention.

What is claimed is:

1. A handheld electronic device, comprising:

a housing having lateral dimensions;

a substantially rectangular ground plane element having lateral dimensions substantially equal to the lateral dimensions of the housing, wherein portions of the rectangular ground plane element define a dielectric-filled rectangular slot at one end of the rectangular ground plane element; and

first and second antennas having respective first and second antenna resonating elements, wherein the first antenna comprises a hybrid planar-inverted-F and slot antenna in which the first antenna resonating element comprises a planar resonating element that is located above the slot, wherein the planar resonating element comprises an isolation element that resonates at a common frequency with the second antenna and reduces interference between the second antenna and the first antenna during simultaneous operation of the first and second antennas.

2. The handheld electronic device defined in claim **1** wherein the second resonating element comprises a conductive strip that resonates in a 2.4 GHz communications band and wherein the isolation element helps to isolate the first and second antennas in the 2.4 GHz communications band.

3. The handheld electronic device defined in claim **1** further comprising a first transceiver circuit and a second transceiver circuit, wherein the first antenna and the first transceiver circuit are configured to operate in a first communications frequency range that includes at least 850 MHz and 900 MHz cellular telephone bands and a second communications frequency range that includes at least 1800 MHz and 1900 MHz cellular telephone bands, wherein the second antenna resonating element comprises a conductive strip that resonates in a 2.4 GHz communications band, and wherein the isolation element helps to isolate the first and second antennas in the 2.4 GHz communications band.

4. The handheld electronic device defined in claim **1** further comprising a first transceiver circuit and a second transceiver circuit, wherein the first antenna and the first transceiver circuit are configured to operate in a first communications frequency range that includes at least 850 MHz and 900 MHz cellular telephone bands and a second communications frequency range that includes at least 1800 MHz and 1900 MHz cellular telephone bands, wherein the second antenna resonating element comprises a conductive structure that resonates in a 2.4 GHz communications band, wherein the isolation element helps to isolate the first and second antennas in the 2.4 GHz communications band, and wherein the first antenna resonating element comprises a first arm that serves as the isolation element and a second arm that resonates in the second communications frequency range.

5. The handheld electronic device defined in claim **1** further comprising a first transceiver circuit and a second transceiver circuit, wherein the first antenna and the first transceiver circuit are configured to operate in a first communications frequency range that includes at least 850 MHz and 900 MHz cellular telephone bands and a second communications frequency range that includes at least 1800 MHz and 1900 MHz cellular telephone bands, wherein the second antenna resonating element comprises an L-shaped metal strip that resonates in a 2.4 GHz communications band, wherein the isolation element helps to isolate the first and second antennas in the 2.4 GHz communications band, wherein the first antenna resonating element comprises a shorter arm that serves as the isolation element and a longer arm that resonates in the second communications frequency range, and wherein the slot is configured so that the first antenna resonates in the second communications frequency range.

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